PROPERTIES OF THE X(3872)

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We report recent results on the properties of the X(3872) produced via the $B^+ \to K^+ X(3872)$ decay process in the Belle detector. We present constraints on possible charmonium-state assignments for this particles.

1. Introduction

A first step in understanding the X(3872) particle that was recently discovered by Belle[1] is to determine its J^{PC} quantum numbers. Here, we survey possible assignments and properties of the most likely candidates. We restrict our considerations to 0^{++} and 1^{--} $\pi^+\pi^-$ systems[2] and scenarios where the relative orbital angular momentum of the $\pi^+\pi^-$ and J/ψ is $L \leq 3$. In this report we concentrate on possible charmonium assignments, and only those where decays to $D\overline{D}$ are forbidden or expected to be strongly suppressed. For the case of a 0^{++} dipion, there are three charmonium possibilities: the $h_c^{'}(2^1P_1)$ and two triplet D-wave states, the $\psi_2(^3D_2)$ and $\psi_3(^3D_3)$. For the 1^{--} dipion case, there are also three possibilities: the $\eta_c^{''}$, the $\chi_{c1}^{'}$ and the $\eta_{c2}(^1D_2)$. For these assignments, the $\pi^+\pi^- J/\psi$ decay would violate isospin and should be strongly suppressed.

2. Search for X(3872)$\to \gamma\chi_{c2}$ (χ_{c1})

The Wigner-Eckart theorem says that the widths for $\psi_2 \to \pi^+\pi^- J/\psi$ and $\psi_3 \to \pi^+\pi^- J/\psi$ should both be equal to $\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi)$. This has been recently measured by BESII[3] and CLEO-c[4] to be $80 \pm 32 \pm 21$ keV and $\leq$ 55 keV (90% CL), respectively. The results are in some contradiction with each other. For the following discussion we conservatively assume an upper limit derived from the larger BES number of $\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi) < 129$ keV.

Calculations of the $\gamma\chi_{c1}$ width for an M=3872 MeV ψ_2 range from 207 keV[5] to 360 keV[6]. The 90% CL upper limit of

$$\frac{\Gamma(X \to \gamma\chi_{c1})}{\Gamma(X \to \pi^+\pi^- J/\psi)} < 0.89 \tag{1}$$

that was reported in Ref.[1] contradicts these expectations for the ψ_2.

Barnes and Godfrey[6] observe that although $\psi_3 \to D\overline{D}$ is allowed for a 3872 MeV ψ_3, this mode is suppressed by an $L = 3$ centrifugal barrier and the total ψ_3 width may be less than the $\Gamma < 2.3$ MeV experimental upper limit[1]. These authors, and also Eichten, Lane and Quigg[5], propose the ψ_3 as a charmonium candidate for the X(3872).

For an M=3872 MeV ψ_3, the calculated $\gamma\chi_{c2}$ widths range from 299 keV[5] to 370 keV[6]. Thus, the partial width for $\psi_3 \to \gamma\chi_{c2}$ is expected to be more than twice that for $\psi_3 \to \pi^+\pi^- J/\psi$. We performed a search for $X \to \gamma\chi_{c2}$ that followed closely the procedure used for the $\gamma\chi_{c1}$ limit reported in Ref.[1]. We require one of the $\gamma J/\psi$ combinations to satisfy 444 MeV $< (M_{\gamma\ell^+\ell^-} - M_{\ell^+\ell^-}) <$ 469 MeV. The M_{bc} and ΔE signal regions are $|M_{bc} - 5.28| < 0.009$ GeV and -0.04 $< \Delta E <$ 0.03 GeV.

We use the $B \to K\psi^{'}; \psi^{'} \to \gamma\chi_{c2}$ decay chain as a normalization reaction. The signal-band projections of M_{bc} and $M_{\gamma\chi_{c2}}$ for the $\psi^{'}$ region are shown in Figs. 1 (left) and (right), respectively, together with curves that show the results of the fit. The fitted signal yield is 18.3 ± 5.2 events, where, based on known branching fractions, we expect 12 ± 3 events.

Figure 2 show the same projections for events in the X(3872) region, where there is no apparent signal. An unbinned fit produces a signal yield of $2.9 \pm 3.0 \pm 1.5$ events, where the first error is statistical and the second systematic. The latter is estimated by the changes that occur when the input parameters to the fit are varied over their allowed range of values.

The ratio of the $X \to \gamma\chi_{c2}$ and the $X \to \pi^+\pi^- J/\psi$ partial widths and its 90% CL upper limit are

$$\frac{\Gamma(X \to \gamma\chi_{c2})}{\Gamma(X \to \pi^+\pi^- J/\psi)} = 0.42 \pm 0.45 \pm 0.23 < 1.1(90\%CL), \tag{2}$$

where the second quoted error is the quadratic sum of the systematic uncertainties in acceptance, the branching fractions and variations in the $\gamma\chi_{c2}$ event yield for different fitting methods.

3. Search for $X \to \gamma J/\psi$

The $\chi_{c1}^{'}$ is expected to be near 3968 MeV, well above the $D\overline{D}^*$ threshold, and its width is expected to be hundreds of MeV[5]. If potential models are

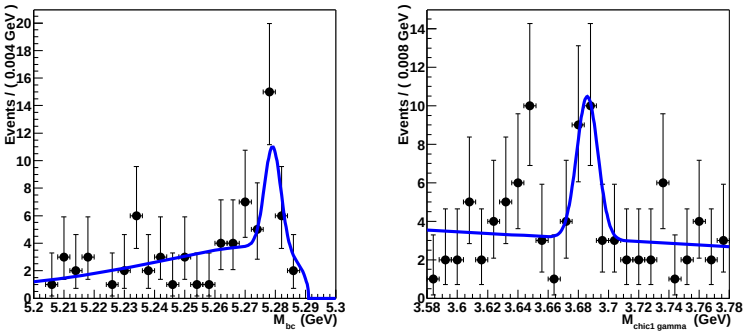

Figure 1. Signal-band projections of M_{bc} (left) and $M_{\gamma\chi_{c2}}$ (right) for events in the $\psi^{'}$ region with the results of the unbinned fit superimposed.

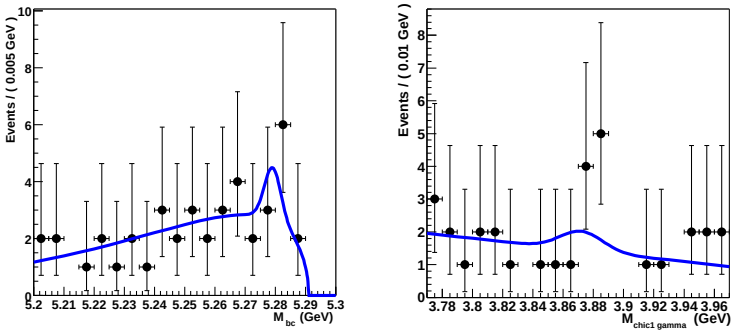

Figure 2. Signal-band projections of M_{bc} (left) and $M_{\gamma\chi_{c2}}$ (right) for events in the X(3872) region with the results of the unbinned fit superimposed.

wrong and the $\chi_{c1}^{'}$ is below the $D\overline{D}^{*}$ threshold at 3872 MeV, it could conceivably be narrow and $\pi^{+}\pi^{-}J/\psi$ decays might be significant, even though these would violate isospin. In this case, the $\gamma\psi^{'}$ and $\gamma J/\psi$ transitions would be important and almost certainly have larger partial widths than that for the $\pi^{+}\pi^{-}J/\psi$ mode. We searched for the $X \to \gamma J/\psi$ decay mode.

We select $B^{+} \to K^{+}\gamma J/\psi$ event candidates using the criteria given in ref.[1]. The $B^{+} \to K^{+}\gamma J/\psi$ channel is dominated by $B^{+} \to K^{+}\chi_{c1}$; $\chi_{c1} \to \gamma J/\psi$ decays and we use this as a calibration reaction. We define a χ_{c1} window for $\gamma J/\psi$ masses within 20 MeV of the nominal χ_{c1} mass. Figure 3 shows the signal-band projections for M_{bc} (left), $M_{\gamma J/\psi}$ (center)

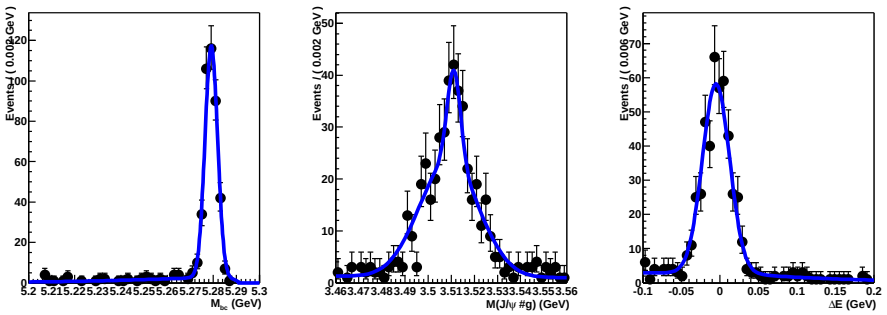

Figure 3. Signal-band projections of M_{bc} (left), $M_{\gamma J/\psi}$ (center) and ΔE (right) for events in the χ_{c1} region with the results of the unbinned fit superimposed.

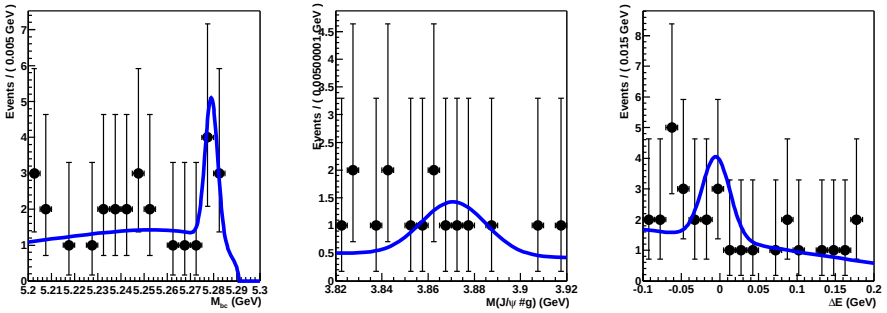

Figure 4. Signal-band projections of M_{bc} (left), $M_{\gamma J/\psi}$ (center) and ΔE (right) for events in the X(3872) signal region with the results of the unbinned fit superimposed.

and ΔE (right) for events in the χ_{c1} region with the results of a three-dimensional unbinned fit superimposed. The fitted number of events is 470 ± 24.

We define an $X \to \gamma J/\psi$ signal region to be $|M(\gamma J/\psi) - 3872\,\mathrm{MeV}| < 26$ MeV. Figure 4 shows the same projections for events in the X(3872) signal region. Here there is no strong evidence for a signal: the fit gives a 2.2σ signal yield of 7.7 ± 3.6 events. The resulting limit is

$$\frac{\Gamma(X \to \gamma J/\psi)}{\Gamma(X \to \pi^+\pi^- J/\psi)} = 0.22 \pm 0.12 \pm 0.06 < 0.40(90\%CL), \qquad (3)$$

where the second quoted error is systematic and includes uncertainties in acceptance, the branching fractions and variations in the $\gamma J/\psi$ event yield

for different fitting methods.

4. Helicity angle distribution for $1^{+-}h_c^{'}$

We define $\theta_{J/\psi}$ as the angle between the J/ψ and the negative of the K^+ momentum vectors in the X(3872) rest frame in the decay $B \to XK; X \to \pi^+\pi^- J/\psi$. The $|\cos\theta_{J/\psi}|$ distribution for X(3872) events with $m_{\pi^+\pi^-} > 0.65$ GeV is shown as data points in Fig. 5. The smooth dotted curves are polynomials that are fit to sideband-determined backgrounds.

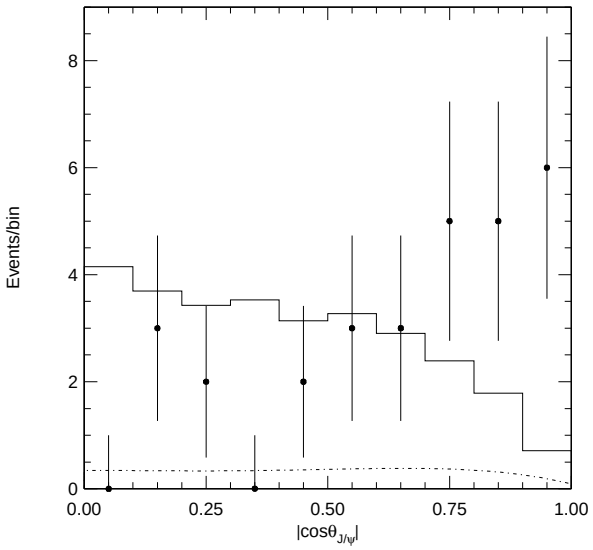

Figure 5. The measured $|\cos\theta_{J/\psi}|$ distribution. The superimposed histogram is the normalized MC distribution for the 1+- hypothesis. Here $\chi^2/dof = 75/9$.

Figure 5 shows a comparison of the measured $|cos\theta_{J/\psi}|$ distribution with a MC sample generated with a $J^{PC} = 1^{+-}$ hypothesis. Here the expected $|\cos\theta_{J/\psi}|$ distribution has a $\sin^2\theta_{J/\psi}$ dependence that goes to zero at $\cos\theta_{J/\psi} = 1$, where the data tend to peak. This makes the overall χ^2 quite poor, χ^2/dof is 75/9, and enables us to rule out the $1^{+-}(h_c^{'})$ hypothesis for the X(3872) with high confidence.

5. Summary

None of the six charmonium candidate states comfortably fit the measured properties of the X(3872). The 90% CL branching fraction upper limit for $B(X(3872) \to \gamma\chi_{c2})$ decay is 1.1 times that for $\pi^+\pi^- J/\psi$. This conflicts with theoretical expectations for the case where the X(3872) is the $3^{--}\psi_3$.

The possibility that the X(3872) is the $1^{++}\chi_{c1}^{'}$ is made improbable by the limit $B(X \to \gamma J/\psi) < 0.4B(X \to \pi^+\pi^- J/\psi)$. The former would be an allowed E1 transition with an expected width of $\Gamma_{\gamma J/\psi} \sim 10$ keV[6]. The latter would be an isospin-violating transition; other isospin violating transitions in the charmonium system have widths that are less than 1 keV.

An analysis of the $\theta_{J/\psi}$ helicity angle distribution eliminates the $1^{+-}(h_c^{'})$ hypothesis with a high degree of confidence.

The $0^{-+}(\eta_c^{''})$ mass differs from that of the $\psi(3S)$ by hyperfine splitting and can be reliably expected to be about 50 MeV (or less) below that of the $\psi(3S)$, which is at 4030 MeV. Moreover, even if it were as low as 3872 MeV, the width is expected to be some 10's of MeV, similar to that of the η_c and wider than the 2.3 MeV upper limit for the X(3872). For $2^{-+}(\eta_{c2})$, the $\eta_{c2} \to \pi^+\pi^-\eta_c$ and γh_c decays are allowed and expected to have widths in the range of 100's of keV[6], and much larger than that for the isospin-violating $\pi^+\pi^- J/\psi$ mode. If the X(3872) were the η_{c2}, the total exclusive branching fraction for the $B^+ \to K^+\eta_{c2}$ decay, which is non-factorizable and suppressed by an $L = 2$ barrier, would be anomalously large.

References

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